

Genesis of Roccastrada volcanic rocks (central Italy): inferences from melt inclusions analyses

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ABSTRACT. — Melt inclusions analyses were carried out on quaternary rhyolitic rocks from Roccastrada volcano (Tuscany, central Italy). The data confirm the anatectic origin for the magma that gave rise to the Roccastrada volcanism and evidenced no involvement of basic component in the petrogenesis of these melts. Similar compositions of melt inclusions trapped in phenocrysts and of residual glass matrix of Roccastrada rhyolites, suggest that these melts did not undergo to important differentiation processes after their generation. Quartz, sanidine, plagioclase and cordierite crystallized from peraluminous melts, at temperatures in the range of 755-820°C, and at pressure of about 150-180 MPa.

di Roccastrada, suggeriscono che questi fusi non hanno subito processi di differenziazione significativi nei momenti successivi alla loro generazione. Quarzo, sanidino, plagioclasio e cordierite sono cristallizzati da fusi peraluminosi, a temperature nell'intervallo 755-820°C, e a pressioni di circa 150-180 MPa.

KEY WORDS: *Roccastrada, melt inclusions, microthermometric measurements, crustal anatexis.*

INTRODUCTION

RIASSUNTO. — Sono state studiate le inclusioni silicatiche nei cristalli nelle rocce dell'apparato vulcanico di Roccastrada (Toscana, Italia centrale). I dati raccolti confermano che il magma che ha dato origine al vulcanismo di Roccastrada si è originato per anatessi. Inoltre l'esame di questi dati permette di escludere il coinvolgimento di un termine basico nella petrogenesi di questi fusi. Le composizioni delle inclusioni silicatiche intrappolate nei cristalli e dei vetri residuali della massa di fondo delle rioliti

Since Middle Miocene, the Northern sector of the Apennine belt was affected by the emplacement of silicic plutonic rocks at relatively shallow depth in the continental crust and by volcanic activity that produced mainly silicic and crustal derived potassic rocks. These intrusive rocks and volcanic products are commonly known in the literature as the Tuscan Magmatic Province (PMT, Innocenti *et al.*, 1992 and references therein).

The silicic magmas of the PMT are considered to have been generated by anatectic

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processes occurring in the adriatic continental crust and affected by widespread mixing with mantle-derived liquids (Serri *et al.*, 1991). An alternative two-stage petrogenetic model is invoked by Poli (1992) to explain geological, petrographical and geochemical characteristic of some granitoids of the PMT. During the first stage, a mixing plus crystal fractionation process involves a crustal peraluminous magma and a basic magma of probable subcrustal origin. During the second stage, a simple mixing process between the same crustal peraluminous magma and different evolved magmas, derived from the basic magma during the first stage, occurs. In this framework the Roccastrada products could represent the acid end-member (Poli, 1992), originated by pure crustal anatexis (Giraud *et al.*, 1986). Peculiar geochemical features of the products induce Giraud *et al.* (1986) to interpret the formation of these rhyolites not simply by partial melting of a Paleozoic garnet-bearing micashist source, but with a selective contamination of pure antecitic melts by fluids derived from the deeper crust.

The Roccastrada volcanic complex consists exclusively of cordierite-bearing rhyolitic lavas, outpoured along a regional fault system (Mazzuoli, 1967) about 2.5 Ma ago (Innocenti *et al.*, 1992). Pinarelli *et al.* (1989), on the basis of geochemical data, distinguished these products into two groups, the High-Rubidium rhyolites (HRb) and the Low-Rubidium rhyolites (LRb), cropping out at East and at West of the Mt. Alto ridge, respectively (fig. 1). These geochemical characteristics associated to $^{87}\text{Sr}/^{86}\text{Sr}$ value variations are probably related to a different degree of partial melting of the crustal source (Pinarelli *et al.*, 1989; Innocenti *et al.*, 1992).

In this paper we present chemical data on melt inclusions (MI) trapped in phenocrysts of these rhyolites. During magmatic crystallization droplets of melt may be trapped as a primary inclusions in phenocrysts of volcanic rocks and therefore they may be representative of the melt from which the phenocrysts grew (Clocchiatti, 1971; Beddoe-

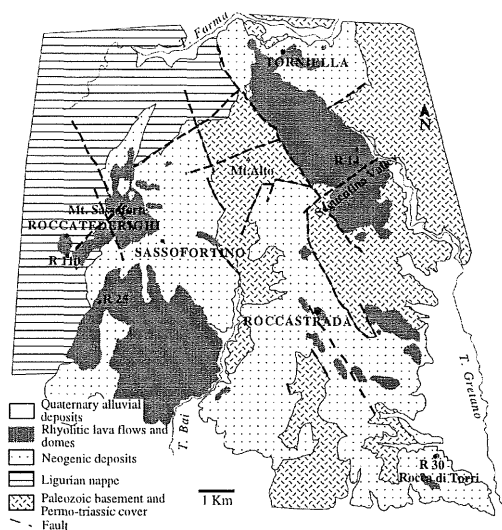


Fig. 1. – Geological sketch of the studied area

Stephens *et al.*, 1983; Clocchiatti and Massare, 1985; Anderson *et al.*, 1989; Hervig and Dunbar, 1989). We have analyzed MI in quartz, cordierite and feldspar phenocrysts, with the aim to collect information on the temperature and pressure of crystallization of Roccastrada magma and possibly on the genesis and the evolution of these magmas.

GEOLOGICAL AND VOLCANOLOGICAL OUTLINES

The Roccastrada volcanic complex is located in South Tuscany at about 40 km NW of the Mount Amiata Quaternary volcano, and it is distributed over an area of about 100 km². The volcanites mainly rest on Triassic-Paleozoic formations, belonging to the Monticiano-Roccastrada tectonic units (Costantini *et al.*, 1988); only in the western and southern sector of the area, the lavas overlie the Ligurian units and Neogenic deposits. These products form numerous outcrops, situated west and east of the Monte Alto ridge, which is made up of quartzites of Trias (fig. 1). The volcanic complex is characterized by numerous lava domes associated with a few lava flows. There is no evidence of explosive activity in the

TABLE 1
Whole rock analyses and CIPW norms of
selected samples

Sample	R25	R14	R110	R30
SiO ₂	74.19	74.11	73.75	75.17
TiO ₂	0.27	0.23	0.29	0.23
Al ₂ O ₃	13.82	14.31	13.99	13.85
Fe ₂ O ₃	2.24	2.01	2.23	2.00
MnO	0.04	0.04	0.04	0.04
MgO	0.40	0.25	0.52	0.24
CaO	1.03	0.89	1.00	0.82
Na ₂ O	2.89	2.95	2.74	2.81
K ₂ O	4.98	5.04	5.30	4.69
P ₂ O ₅	0.14	0.18	0.14	0.13
CIPW norm				
Q	34.66	34.59	34.19	37.81
C	2.12	2.78	2.26	2.91
or	28.95	29.19	31.32	27.3
ab	24.11	24.45	23.19	23.44
an	4.1	3.14	4.05	3.17
hy	2.55	2.05	3.08	2.03
mt	0.99	0.88	1.12	0.89
il	0.51	0.44	0.55	0.44
ap	0.33	0.43	0.33	0.31
aq	1.68	2.03		2.28

Roccastrada area, except for local explosions occurring during dome emplacement, which gave rise to very limited pyroclastic deposits (Rocca di Torri and Torniella units).

The main volcanic structures recognizable west of M. Alto are (fig. 1): 1) the large lava dome of Mt. Sassoforte (about 2.7 km²) dislocated by two fault systems; 2) the large lava flow extending for about 11 km² south of Mt. Sassoforte with a thickness ranging between 2 and 10 meters, rarely exceeding 10 meters; 3) the small dome of Roccatederighi (0.2 km²) with subvertical flow-bands in the outer portions and a massive lava core characterized by large sanidine phenocrysts and altered cordierite crystals of 0.3/0.5 cm. On the Eastern flank of M. Alto the volcanites are characterized by a series of lava domes and lava flows outpoured from fractures with a NW-SE direction (fig. 1). In the northern sector (Torniella Area, fig. 1) small, occasionally isolated lava domes with scarce and limited, usually autobrecciated, lava flows are found. In the Seguntina Valley lavas reach a maximum

thickness of about 100 meters. In this area the lavas, generally glassy, are intensely autobrecciated and affected by oxidation processes. From Roccastrada village to Rocca di Torri, small lava domes are roughly aligned along a NW-SE direction. This trend corresponds to the main Apenninic fault system, not easily recognizable in the field in this area due to the presence of a clay-rich Neogenic deposit.

Analyses of aerial photos and field data revealed that the majority of the Roccastrada volcanites were erupted along fractures with NW-SE Apenninic trend. The largest volumes of lavas, however, were emitted in correspondence of Mt. Sassoforte and the Seguntina Valley, where the Apenninic and Antiapenninic regional trends (NW-SE and NE-SW) match. Furthermore, the field observations suggest that in late Pliocene time, during the volcanic activity which gave rise to the Roccastrada volcanites, the morphology was very similar to the present one. Probably Mt. Alto ridge already was representing at that time a morphological high that conditioned the distribution of the outpoured lava. Relationships between the tectonics and volcanism indicate that the tectonic activity along these fault systems continued after the lava emplacement.

ANALYTICAL METHODS

Fragments of samples were pulverized and analyzed by X-ray fluorescence for major elements with the method described by Franzini *et al.* (1975).

Crystals selected for microthermometric and compositional studies were prepared in double polished wafers. Several heating experiments on quartz phenocrysts were carried out with an optical heating stage designed in the Vernadsky Institute of Geochemistry of Moscow (described by Sobolev *et al.*, 1980). The temperature was measured with a Pt-Pt₉₀Rh₁₀ thermocouple and controlled by the melting point of pure gold and silver. The rate of heating was varied as a

function of the rate of transformation in inclusions. Due to the high viscosity of the melt, a very low rate of heating and long plateau were used: temperatures of 800°C were reached only after 6 to 10 hours. At the attainment of homogenization the inclusions were quenched in a He atmosphere. Quenched crystals were mounted in epoxy and polished to the point of exposure of the inclusion.

Quantitative analyses of MI, glass matrix and minerals were performed using the SEM-EDS technique in the Electron Microscopy Laboratory of the Dipartimento di Scienze della Terra di Pisa (Philips XL30 with EDAX DX4) at 20 kV accelerating energy, 500 nm beam diameter, 100s live time. On glasses a raster area of about 10×10 microns was analyzed to reduce Na loss. On each MI 3 to 5 analyses were performed to check their compositional homogeneity. Well known minerals and glasses were used as reference standards (Marianelli and Sbrana, 1998).

PETROGRAPHY AND MINERAL CHEMISTRY

Chemical analyses of 60 samples from the different outcrops confirm the compositional homogeneity indicated by previous authors (Mazzuoli, 1967; Pinarelli *et al.*, 1989). All the samples show a rhyolitic composition, have a high peraluminous index ($Al_2O_3/CaO+Na_2O+K_2O > 1.4$) and normative corundum. The Roccastrada products represent the most felsic rocks of all the PMT volcanics. In Table 1 the chemical analyses of the whole rocks of the selected samples for the MI analyses are reported.

The Roccastrada rhyolites are characterized by porphyritic texture, with about 35-40% of phenocrysts consisting of sanidine, quartz, plagioclase, biotite and cordierite. Apatite, zircon, ilmenite and sillimanite (as an inclusion in cordierite) are present as accessory phases. Some euhedral crystals of garnet are observed in the groundmass together with numerous metasedimentary xenoliths.

Phenocrysts are set in a groundmass showing

perlitic-fluidal, or microgranophyric textures. The Roccatederighi lava dome is generally made up of microcrystalline lava with a well-developed granophyric texture, especially in the inner portion of the dome.

Lavas from different outcrops do not show significant textural and modal differences; only the phenocrysts from the Roccatederighi lava dome have larger sizes than those in the other rocks. Main characteristics of the main mineral phases are here briefly reported.

Quartz the phenocrysts of this mineral are generally characterized by embayed rims, whereas the microphenocrysts usually have an euhedral habits.

Sanidine occurs in large euhedral crystals, often fractured; some crystals show resorption rims. Somewhere it shows poikilitic texture with plagioclase microcrystals, biotite and rarely cordierite inclusions. In the lava from the inner portion of the Roccatederighi dome, the phenocrysts of sanidine can reach 8 cm in length (Balducci and Leoni, 1981). The Or content significantly increases rimward (Table 2).

Plagioclase is commonly present either in glomerophyric aggregates or individual crystals. Sometimes rims are mantled by sanidine. Both individual and cumulus phenocrysts show cores partially resorbed. Frequently, plagioclase includes glass, quartz, biotite and zircon. The composition ranges between An₂₆ and An₆₀ (Table 2) with direct and oscillatory zoning from core to more Ab-rich rims. Resorption cores of sample R110 show high Ca-content (An₇₈). Plagioclase cadacrysts included in sanidine, and rarely in cordierite, cover the same compositional range of the phenocryst rims.

Biotite occurs both as euhedral crystals and anhedral oxidized crystals, and often includes ilmenite, zircon and apatite. Phenocrysts are homogenous, characterized by high aluminous contents (Table 2).

Cordierite generally represents 1-2 vol.% of the rock and occurs as euhedral twinned crystals. In devitrified lavas, cordierite is always completely altered, especially in the inner portion of the Roccatederighi dome,

TABLE 2

Selected SEM-EDS analyses of the main mineral phases

sample	sanidine	sanidine	sanidine	sanidine	sanidine	sanidine	sanidine	sanidine	sanidine	sanidine	sanidine	sanidine	sanidine	sanidine
	R-25 rim	R-25 rim	R-25 core	R-25 rim	R-14 core	R-14 rim	R-14 core	R-14 rim	R-110 core	R-110 rim	R-110 rim	R-110 rim	R-30 core	R-30 rim
SiO ₂	65.5	65.8	65.2	65.0	66.3	65.4	65.9	65.4	65.7	66.6	65.5	65.9	66.4	66.9
Al ₂ O ₃	19.2	19.2	19.2	19.2	19.3	19.4	19.2	19.2	19.1	19.3	19.3	19.4	19.2	19.2
CaO	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.3	0.0	0.2	0.2
Na ₂ O	2.8	2.8	3.1	2.8	3.5	3.0	4.1	3.0	2.9	2.7	2.8	2.7	3.0	2.8
K ₂ O	12.3	12.1	12.2	12.8	11.2	11.8	10.8	12.3	11.7	11.8	12.1	12.0	11.8	11.4
An	0.9	0.9	1.2	1.1	0.9	0.7	0.5	0.8	0.9	1.2	1.4	0.0	1.1	0.8
Ab	25.8	25.5	27.5	24.9	32.3	27.3	36.4	26.9	27.2	25.4	25.6	25.2	27.7	26.9
Or	73.3	73.6	71.3	74.0	66.9	71.9	63.1	72.3	71.9	73.5	73.0	74.8	71.2	72.3

sample	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase	plagioclase
	R-25 core	R-25 intermediate	R-25 rim	R-25 core	R-110 rim	R-110 int.	R-110 core	R-110 resorbed core	R-110 core	R-110 rim	R-14 rim	R-14 core	R-30 core	R-30 rim
SiO ₂	54.8	60.9	60.7	55.3	61.2	60.4	56.6	48.6	54.5	61.7	62.3	57.4	54.0	62.2
Al ₂ O ₃	29.0	24.9	24.7	28.8	24.3	24.8	27.6	32.6	29.1	24.3	24.5	27.4	29.5	23.8
FeO	0.1	0.1	0.1	0.0	1.d.	1.d.	0.1	1.d.	0.1	1.d.	0.1	1.d.	0.1	1.d.
CaO	11.2	6.4	6.0	10.2	6.1	7.0	9.9	15.7	10.7	5.6	5.4	9.3	12.1	5.1
Na ₂ O	4.9	7.2	7.6	5.3	7.3	6.8	5.3	2.4	5.3	7.3	7.8	6.0	4.4	7.3
K ₂ O	0.3	0.8	0.9	0.4	1.0	0.8	0.5	0.1	0.3	1.1	0.9	0.4	0.2	0.9
An	54.9	31.5	28.7	50.4	29.8	34.7	49.5	78.1	51.6	27.7	26.3	45.3	59.5	26.2
Ab	43.2	63.6	66.1	47.3	64.4	60.7	47.7	21.4	46.4	65.6	68.8	52.7	39.1	68.2
Or	1.9	4.9	5.3	2.3	5.7	4.6	2.8	0.5	2.0	6.6	4.9	2.0	1.3	5.6

sample	biotite	biotite	cordierite	cordierite	cordierite	cordierite	cordierite	cordierite	cordierite	cordierite	cordierite	cordierite	cordierite	cordierite
	R-25 core	R-25 rim	R-25 core	R-25 rim	R-25 rim	R-14 rim	R-14 core	R-14 core	R-14 rim	R-30 core	R-30 rim	R-110 core	R-110 rim	R-110 rim
SiO ₂	35.4	35.1	48.8	47.8	47.6	47.5	48.3	48.9	48.3	49.4	48.4	48.6	48.2	48.2
TiO ₂	4.5	4.4	0.2	1.d.	1.d.	0.1	1.d.	1.d.	1.d.	1.d.	1.d.	1.d.	1.d.	1.d.
Al ₂ O ₃	16.3	16.4	33.5	32.4	32.2	32.0	33.2	33.6	32.2	33.4	32.3	33.4	32.4	32.0
FeO	25.3	25.4	7.1	13.2	16.1	14.4	9.4	8.4	14.0	9.0	14.8	8.6	12.3	13.4
MnO	0.2	0.2	0.5	0.7	0.6	0.7	0.4	0.2	0.6	0.2	0.5	0.3	0.4	0.5
MgO	7.1	6.3	9.6	5.5	3.5	4.8	8.2	8.7	4.7	8.3	4.5	8.6	5.9	5.3
CaO	1.d.	1.d.	0.1	0.1	0.1	0.1	0.2	n.d.	n.d.	n.d.	0.0	0.0	n.d.	0.0
Na ₂ O	0.5	0.5	0.1	n.d.	0.3	0.2	0.2	n.d.	n.d.	n.d.	n.d.	0.4	0.2	0.2
K ₂ O	8.8	8.7	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.1	0.2	0.1	0.1	0.1
Fe/(Fe+Mg)	0.7	0.7	0.3	0.6	0.7	0.6	0.4	0.3	0.6	0.4	0.7	0.3	0.5	0.6

All Fe as FeO; 1.d. = below detection limit

where it is completely pinitized and reaches the 8-9 vol.% of modal content. Cordierite phenocrysts usually show abundant inclusions of euhedral biotite, sillimanite, rare plagioclase and rounded quartz. Cordierite shows a wide compositional range ((Fe/Fe+Mg) from 0.34 to 0.73), with a regular increase of Fe-content from core to rim (Table 2). Numerous fluid inclusions characterize the crystal cores (Fe/Fe+Mg < 0.4) whereas well preserved glassy MI are frequent in the outer portions of the crystals.

PETROGRAPHY OF MELT INCLUSIONS

Melt inclusions were studied on phenocrysts of quartz, feldspars and cordierite of samples belonging to both HRb and LRb groups defined by Pinarelli *et al.* (1989). Melt inclusions in quartz (QMI), ranging up to 100-200 microns in diameter, were selected for thermometric and compositional measurements. Compositional analyses were performed also for melt inclusions ($\approx 100 \mu\text{m}$) in cordierite (CMI). The MI in plagioclase and K-feldspar (FMI) are small ($\leq 20 \mu\text{m}$) and only in a few cases are suitable for microanalysis. The shape and size of QMI and the size and amount of bubbles are highly variable. The MI distribution within the crystals is random, but clusters are common. The shape of the inclusions varies, depending on the samples, from spherical to faceted, the latter indicating a tendency to negative crystal forms. Similar glass inclusions in quartz are described by Clacchiatti (1975) and Clacchiatti and Metrich (1977). They suggested that the MI negative crystal shapes result from the maintaining of the quartz crystals at sufficiently high temperatures after the melt entrapment. This process allows localized diffusion of Si within the MI (Chaigneau *et al.*, 1980) and the following evolution of the MI shapes from rounded to negative crystal.

The prevalent type of MI is represented by homogeneous colorless to pale brown glass, with or without bubbles. In some inclusions the

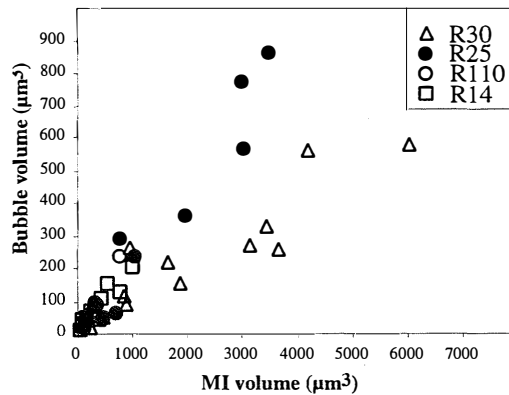


Fig. 2. – Diagram showing the variation of the MI bubble volume versus MI volume (μm^3) for the melt inclusion in quartz phenocrysts. Volume estimations are made assuming the shape of the MI to be spherical.

glass contains randomly oriented microlithes or crystal nuclei, mainly distributed around bubbles. Some inclusions are crowded of minute crystallites, which give a cloudy aspect to the glass. The ($\text{volume}_{\text{bubble}}/\text{volume}_{\text{glass}}$) values of MI is generally constant, except for some samples (i.e. R25 and R14) where this ratio is significant higher (fig. 2). This suggests diffusion and loss of volatiles from the MI, in spite of lack of microcracks. The cloudy aspect of the inclusions of sample R110 completely hides the bubbles at room temperature and therefore measurement of bubbles was not performed. CMI are found in the thick rims of the phenocrysts where the fluid inclusions are not present.

HEATING EXPERIMENTS

The minimum temperature of trapping was estimated by heating the melt inclusion until the homogenization of inclusion was reached (Roedder, 1979). The temperature of homogenization (T_{hom}) is the temperature at which, after melting, the silicate melt expands

TABLE 3

Homogenization temperature of melt inclusions

sample	T _h °C	n	hours
R25	866-881	8	11
R110	784-818	10	10
R14	888-891	2	10
R30	755-805	7	9

Th: temperature of homogenization of MI; n: number of successful runs; hours: mean duration of heating experiments.

to fill the cavity. Because silicate melts are relatively incompressible a pressure correction is negligible (Roedder, 1984) and the trapping and homogenization temperatures are in close agreement.

Daughter crystals in QMI, where present, melted before the disappearance of the vapor bubble, at about 630-690°C. Inclusions homogenized between 755° and 805°C for R30 and in the range between 785 and 820°C for sample R110 (Table 3, fig. 3). Homogenization within 866-891°C was reached for negatively shaped QMI in samples R14 and R25 (Table 3, fig. 3), in which some inclusions never reach homogenization. However, at about 740°C included glass is completely molten in all MI.

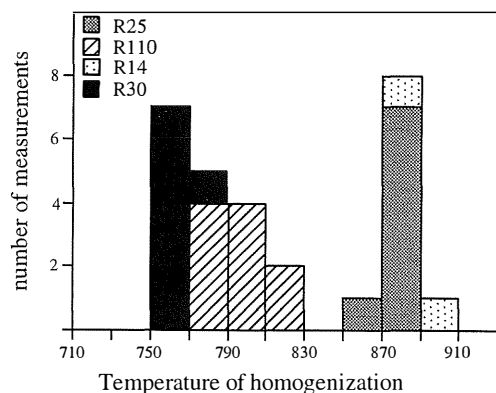


Fig. 3. – Histogram showing the homogenization temperature (°C) of melt inclusions.

CHEMISTRY OF MELT INCLUSIONS

The interpretation of glass inclusion analyses must allow for several potential problems. For example, it is necessary to evaluate the secondary (post trapping) compositional change of the inclusion, due to diffusion or internal host mineral and/or daughter crystal growth. This process and the effect of the heating experiments on the composition of MI have to be taken into account. Therefore, homogenized and quenched MI, and unheated MI were both analyzed, and the results were compared.

Analyses on glassy matrix and both quenched and unheated MI show peraluminous rhyolitic compositions (Tables 4 and 5).

Chemical data on MI show compositions generally more acid than the whole rock except for some inclusions of the sample R110 (fig. 4). Also the QMI of R14 show anomalous silica content in respect to other inclusions (fig. 4). This is probably related to a slow cooling of the crystal-melt system (Manley, 1996).

Electron microprobe analyses on QMI of sample R30 were utilized to estimate the volatile content by the difference method

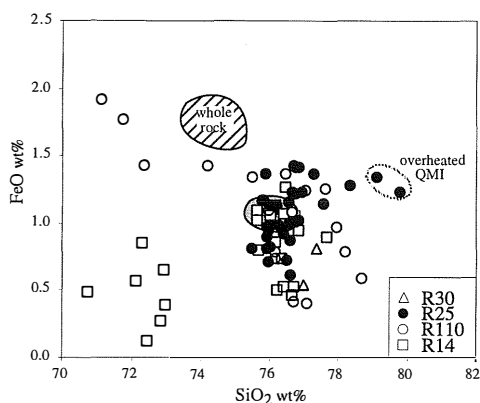


Fig. 4. – FeO vs SiO₂ plot of melt inclusions. The gray field represents the composition of glass matrix, the dashed area represents the whole rock samples.

TABLE 4
Representative SEM-EDS analyses of melt inclusions

sample host	R-25 qz	R-25 qz	R-25 qz	R-25 qz	R-25 qz	R-25 fld	R-25 fld	R-25 fld	R-25 crd.	R-25 crd.	R-25 crd.
SiO ₂	76.8	75.9	76.0	79.8	79.1	77.3	76.7	76.9	76.4	75.8	76.6
TiO ₂	0.1	0.2	0.1	0.0	0.0	0.1	0.2	0.4	0.2	0.2	0.0
Al ₂ O ₃	14.2	13.6	14.1	11.5	11.4	13.0	13.2	12.9	13.4	13.4	13.6
FeO	1.0	1.4	0.8	1.2	1.3	1.4	1.2	1.4	1.0	1.2	0.6
MnO	0.1	0.3	0.0	0.0	0.9	0.1	0.1	0.3	0.1	0.1	0.0
MgO	0.1	0.1	0.0	0.0	0.2	0.1	0.1	0.1	0.2	0.1	0.1
CaO	0.4	0.4	0.5	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.4
Na ₂ O	2.6	2.4	3.1	3.3	3.1	2.5	2.6	2.5	3.6	3.2	3.6
K ₂ O	4.6	5.8	5.3	3.8	3.7	5.3	5.5	5.2	4.9	5.7	5.0

sample host	R-14 qz	R-14 qz	R-14 qz	R-14 fld	R-14 fld	R-14 fld	R-14 crd	R-14 crd	R-14 crd	R-30 qz	R-30 qz
SiO ₂	75.6	72.9	70.7	76.0	76.2	76.5	76.4	76.6	76.4	77.0	77.4
TiO ₂	0.2	0.3	0.2	0.1	0.1	0.1	0.2	0.2	0.0	0.1	0.1
Al ₂ O ₃	13.9	15.7	17.2	13.9	13.5	13.1	14.1	13.5	13.6	13.6	13.7
FeO	1.1	0.3	0.5	1.0	1.1	1.3	0.7	0.5	1.1	0.5	0.8
MnO	0.2	0.2	0.1	0.0	0.1	0.1	0.0	0.0	0.2	0.1	0.0
MgO	0.2	0.1	0.3	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.1
CaO	0.3	0.3	0.5	0.3	0.3	0.2	0.5	0.5	0.4	0.5	0.4
Na ₂ O	3.0	4.7	5.0	2.9	2.9	2.8	4.6	3.1	4.1	3.1	2.8
K ₂ O	5.5	5.6	5.4	5.7	5.8	5.8	3.5	5.5	4.2	5.1	4.8

sample host	R-110 qz	R-110 qz	R-110 qz	R-110 fld	R-110 fld	R-110 fld	R-110 crd	R-110 crd	R-110 crd	R-110 crd	
SiO ₂	71.7	72.4	76.7	78.2	76.4	77.9	75.5	77.0	76.2	77.1	76.0
TiO ₂	0.0	0.1	0.1	0.1	0.4	0.2	0.2	0.2	0.2	0.1	0.2
Al ₂ O ₃	17.1	16.4	13.8	13.6	13.7	12.7	14.0	13.3	13.8	13.3	13.5
FeO	1.8	1.4	1.1	0.8	1.4	1.0	1.3	1.2	0.8	0.4	1.1
MnO	0.0	0.1	0.0	0.2	0.2	0.0	0.2	0.1	0.0	0.0	0.1
MgO	0.2	0.2	0.2	0.1	0.4	0.3	0.4	0.1	0.1	0.0	0.1
CaO	0.8	0.7	0.4	0.4	0.4	0.3	0.3	0.4	0.4	0.5	0.5
Na ₂ O	2.9	3.1	2.8	1.5	2.9	2.7	2.3	2.8	3.2	4.5	3.2
K ₂ O	5.5	5.7	5.0	5.0	4.3	4.9	5.6	4.9	5.3	4.0	5.3

All Fe as FeO. qz: quartz; fld: feldspar; crd: cordierite.

TABLE 5
Averaged EDS analyses of glassy matrix

	R25 SD	R14 SD	R110 SD	R30 SD
n	[10]	[10]	[10]	[10]
SiO ₂	76.0 0.3	75.7 0.2	76.2 0.5	76.6 0.3
TiO ₂	0.1 0.1	0.2 0.0	0.1 0.0	0.1 0.0
Al ₂ O ₃	13.6 0.1	13.8 0.1	13.6 0.1	13.5 0.1
FeO _{total}	1.1 0.1	1.1 0.0	1.2 0.1	1.0 0.0
MnO	0.1 0.0	0.1 0.1	0.1 0.1	0.2 0.0
MgO	0.1 0.1	0.2 0.0	0.2 0.1	0.1 0.0
CaO	0.4 0.1	0.4 0.1	0.4 0.1	0.4 0.1
Na ₂ O	3.0 0.1	3.0 0.1	3.4 0.2	3.0 0.0
K ₂ O	5.5 0.1	5.5 0.0	4.8 0.3	5.1 0.3

n = number of quoted analyses. SD = standard deviation

(Devine *et al.*, 1995). The total oxides at 92-93% (Table 5) allow us to assume at least a 6 wt% of volatiles (mainly H₂O) dissolved in the melt.

DISCUSSION

As shown in fig. 2 and fig. 3, QMI of sample R30, characterized by a small bubble in respect to the inclusion, reached homogenization at 760°C, whereas QMI with larger bubbles (samples R25 and R14) required heating at higher temperatures (higher than 850°C) for complete homogenization. The very high value of SiO₂ (= 79 wt%) observed after

homogenization and quenching of these QMI is probably related to the overheating necessary for homogenization. The overheating could have caused melting of the host phase, with consequent increase of SiO_2 in the QMI. This could be related to the slow cooling history of lavas, which caused irreversible post-trapping changes (e.g. leakage processes, Roedder, 1984) in MI. This is also suggested by the high $\text{volume}_{\text{bubble}}/\text{volume}_{\text{glass}}$ ratio (Lowenstern, 1995). Therefore the T_{hom} obtained for these inclusions can be considered as overestimated. On the basis of the temperature of the last melting of the included glass, however, an evaluation of the minimum temperature of trapping can be deduced for QMI of samples R25 and R14 (temperature of crystallization higher than 740°C).

In order to evaluate the effects of the inclusion-crystal host interaction, the analyzed MI were plotted on ternary diagrams, following the graphical method proposed by Watson (1976). CMI and FMI in phenocrysts were plotted on a CaO-FeO- K_2O diagram (CFK) whereas QMI were plotted on a SiO_2 - Al_2O_3 - K_2O diagram (SAK). On these diagrams lines of liquid evolution, calculated from MI by fractionation of cordierite, feldspar and quartz respectively, were also plotted (fig. 5 and fig. 6).

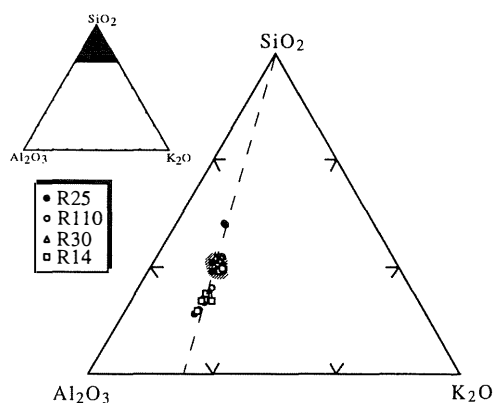


Fig. 5. – SiO_2 - Al_2O_3 - K_2O diagram (SAK) for melt inclusions in quartz phenocrysts. Gray field shows the glass matrix compositions. The dashed line represents the direction of liquid evolution due to quartz fractionation or melting.

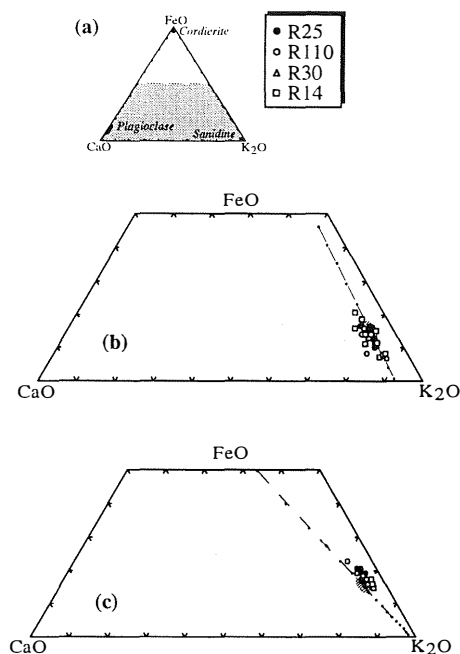


Fig. 6. – FeO-CaO- K_2O diagram (CFK) for melt inclusions (a) compositions of minerals utilized for calculations. (b) MI in cordierite phenocrysts; the gray field represents the glass matrix compositions, the dashed line represents the direction of liquid evolution due to cordierite fractionation or melting (c) MI in feldspar phenocrysts; the gray field represents the glass matrix compositions, the dashed line represents the direction of liquid evolution due to feldspar fractionation or melting.

In the SAK diagram QMI follow the quartz fractionation line with a constant $\text{Al}_2\text{O}_3/\text{K}_2\text{O}$ ratio (fig. 5). Unheated QMI show compositions very similar to the groundmass of samples R25 and R30, whereas they have a lower SiO_2 content in sample R14. This reflects internal crystallization of the host mineral probably following the very low cooling of the sample. Heated QMI (R25) have a higher SiO_2 content, so indicating the overheating and the relative quartz dissolution in the trapped melt. On the contrary, the homogenized and quenched QMI in R110, for which the post trapping transformations were completely recovered by the experiments, seem to record slightly different evolutionary stages

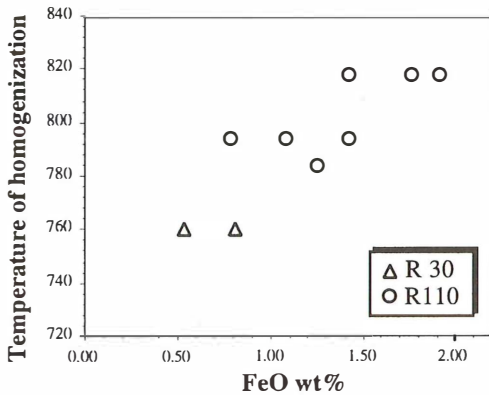


Fig. 7. – Homogenization temperature (°C) vs FeO wt% content of melt inclusions in quartz phenocrysts.

of the trapped liquid for small differences in temperature (fig. 7).

CMI are roughly distributed on the cordierite fractionation line (fig. 6). Therefore MI with lower FeO wt% content and relatively more Mg-rich host (fig. 8), probably derive from crystallization of the host on the inclusion wall. This crystallization, mainly occurring in melt inclusions placed in the core of the crystals, determines the relative evolution of the trapped melt, which should have had an initial composition similar to that of the groundmass (FeO about 1.2 wt%). CMI distribution on the external portions of host phenocrysts, marks the magmatic growth of cordierite on relict

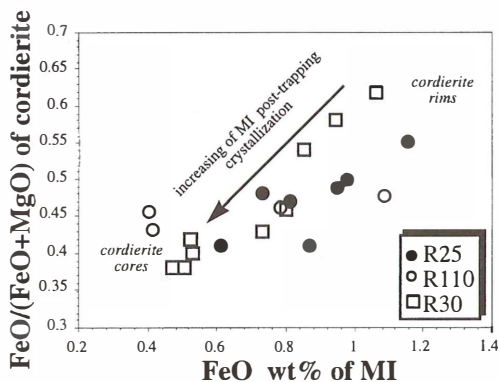


Fig. 8. – FeO wt% content of melt inclusions versus the FeO/(FeO+MgO) ratio of the host cordierite.

cores which show compositions with very low FeO content (fig. 8 and Table 2). Also FMI compositions are affected by crystallization of host mineral on inclusion walls, as deduced by their distribution along the sanidine fractionation line (fig. 6).

Generally the composition of the studied MI is comparable to that of the glass matrix, suggesting that the melt did not evolve significantly after its generation.

Using the empirical model for the solubility of water developed by Moore *et al.*, (1995), the assumed 6 wt% of water dissolved in the Roccastrada melts (sample R30) give minimum a pressure of saturation corresponding to 150-180 MPa.

CONCLUSIONS

During the cooling history the trapped melt may react with the host phase (Clocchiatti, 1975), and the composition of the silicate melt inclusions may be affected by depletion in the chemical components of the crystal host (Watson, 1976). This inclusion-crystal interaction invalidates the direct use of the silicate melt inclusion compositions as representative samples of magmatic liquids (Roedder, 1984). In samples R30 and R110 these transformations are completely recovered by heating and quenching when homogenization of QMI was reached. In these cases we obtained minimum temperatures of crystallization in the range within 755 and 820°C with compositions of melts in equilibrium with crystals at the time of entrapment.

In samples R25 and R14 these transformations are irreversible probably because of a slow cooling history. Therefore, we might argue that for melt inclusions studies only samples characterized by a sufficiently high cooling rate should be selected in order to obtain valid results. Samples R110 and R30, in fact, represent more external portions of lava which underwent a more rapid cooling.

Despite the post trapping evolution of

included melts, there is evidence that crystals have been formed from a melt having a composition very similar to the groundmass and a minimum temperature of 755°C. Only MI of sample R110 record also compositions slightly less evolved and temperatures higher (818°C) than those of the groundmass. This fact implies that the melts do not undergo significant differentiation processes.

The pressure of crystallization of the Roccastrada products, inferred by the minimum pressure of saturation of H₂O in the QMI of sample R30 was relatively low, between 150-180 MPa.

The analyses of MI showed that mafic compositions of MI in phenocrysts are lacking in the Roccastrada rhyolites. This fact, together with the lacking of mafic xenoliths in the Roccastrada products, suggests that the mixing processes between anatectic and subcrustal magmas, observed for the others felsic volcanics of the PMT (e.g. San Vincenzo and M. Amiata; Ferrara *et al.*, 1989; Pinarelli *et al.*, 1989), did not affect these rhyolites. This study, in agreement with the results of previous authors (Peccerillo *et al.*, 1987; Pinarelli *et al.*, 1989), emphasizes that the Roccastrada magmas originated from pure crustal anatexis.

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